Anisotropic flow of strange particles at RHIC

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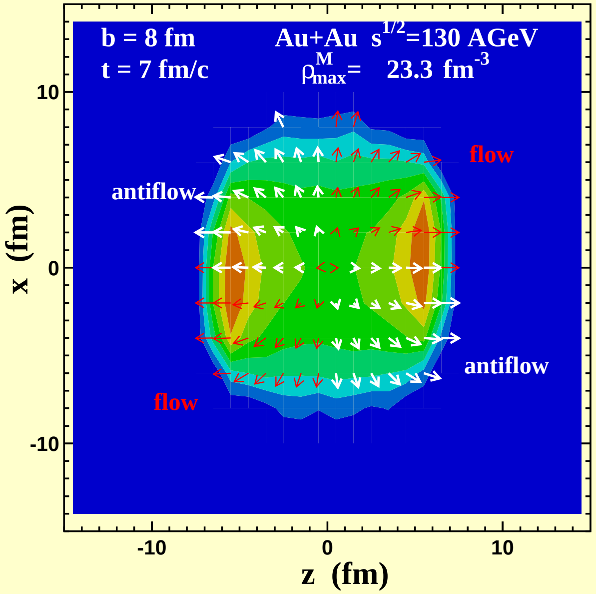
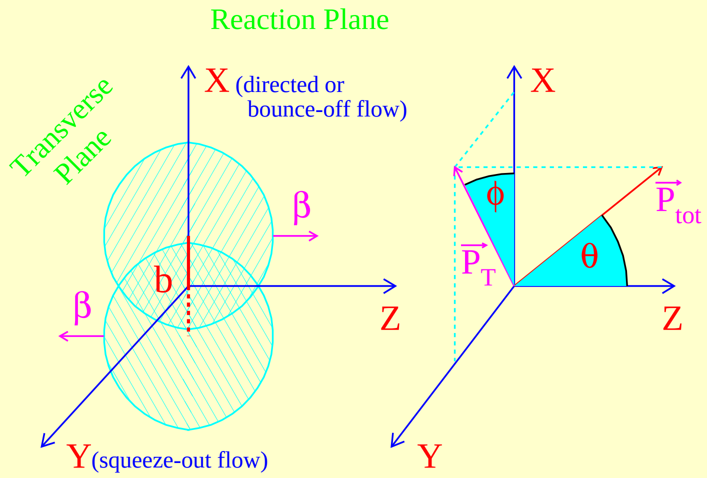
- **Motivation**
- **Directed flow of strange particles at SPS and RHIC**
- **Elliptic flow**
- **Influence of particle freeze-out on the development of elliptic flow**
- **Conclusions**



Transverse Collective Flow of Particles



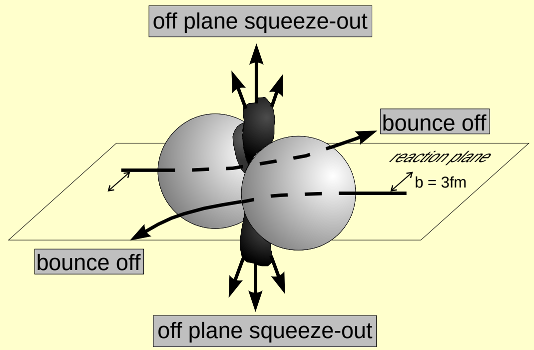
Flow Decomposition:

Transverse flow = Radial + Bounce-off + Squeeze-out

S. Voloshin and Y. Zhang, ZPC 70 (1996) 665

Modern analysis:

Transverse flow =
Radial + Directed + Elliptic + ...
{isotropic}   {anisotropic}



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n\phi'\right)\right)$$

Directed flow:

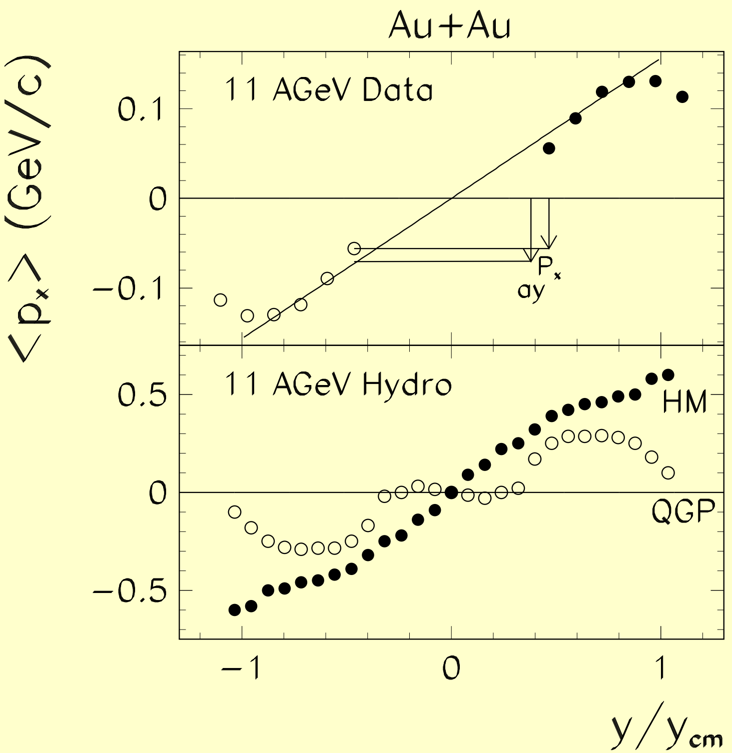
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \equiv \langle \cos\left(\phi'\right)\rangle$$

Elliptic flow:

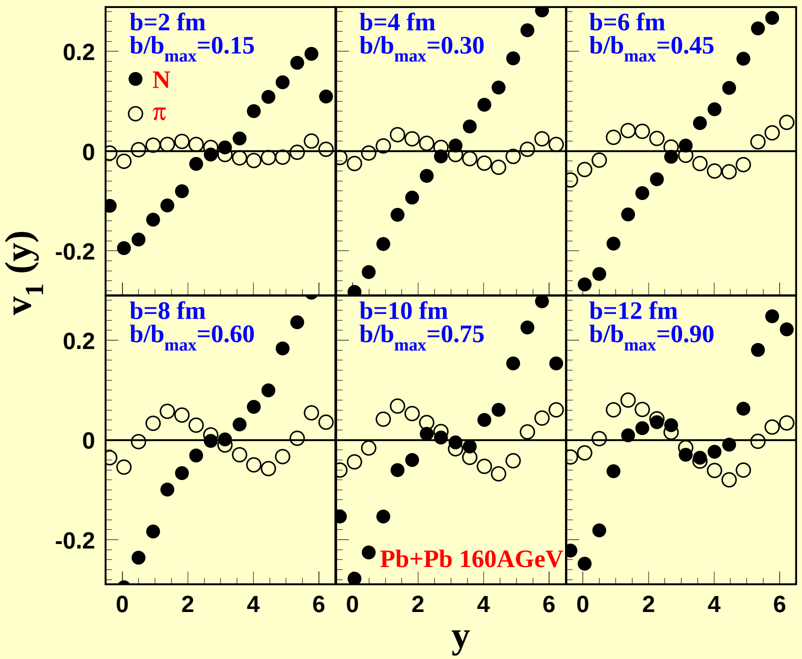
$$v_2 = \left\langle \left(\frac{p_x}{p_T}\right)^2 - \left(\frac{p_y}{p_T}\right)^2 \right\rangle \equiv \langle \cos\left(2\phi'\right)\rangle$$

Softening of Directed Flow

L.P. Csernai, D. Röhrich, PLB 458 (1999) 454



L. Bravina, PLB 334, 49 (1995)
H. Liu, S. Panitkin, N. Xu, PRC 59, 348 (1999)
R.J.M. Snellings *et al.*, PRL 84, 2803 (2000)
L. Bravina *et al.*, PRC 61, 064902 (2000)

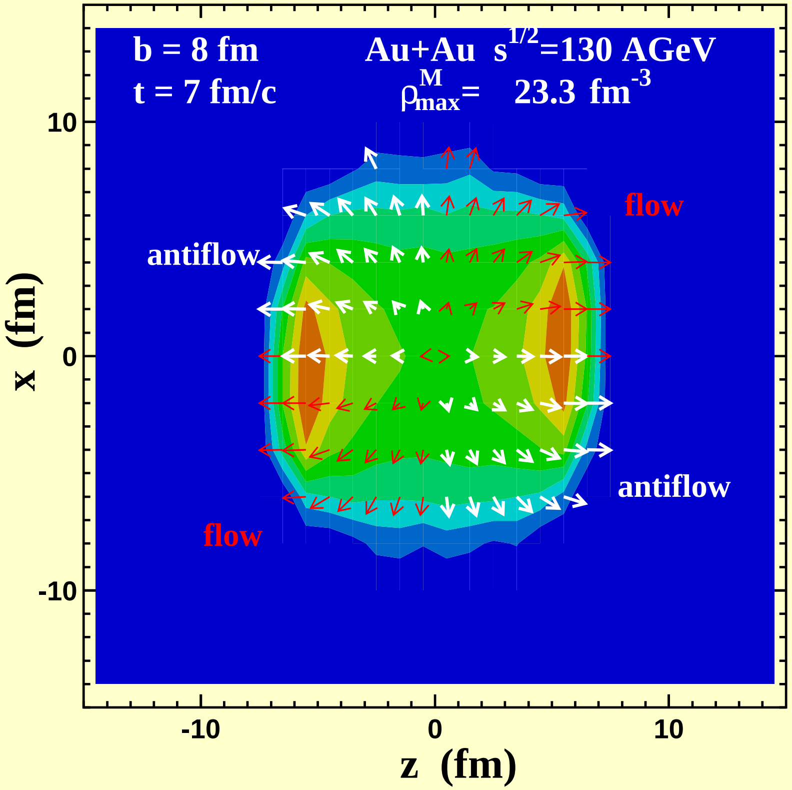


Transition to the Quark-Gluon Plasma $\longrightarrow$ decrease in pressure $\longrightarrow$ softening of the directed flow

Wiggle structure: The effect is more pronounced in peripheral and light-ion collisions, therefore, it cannot be explained by the softening of the EOS because of the formation of strings

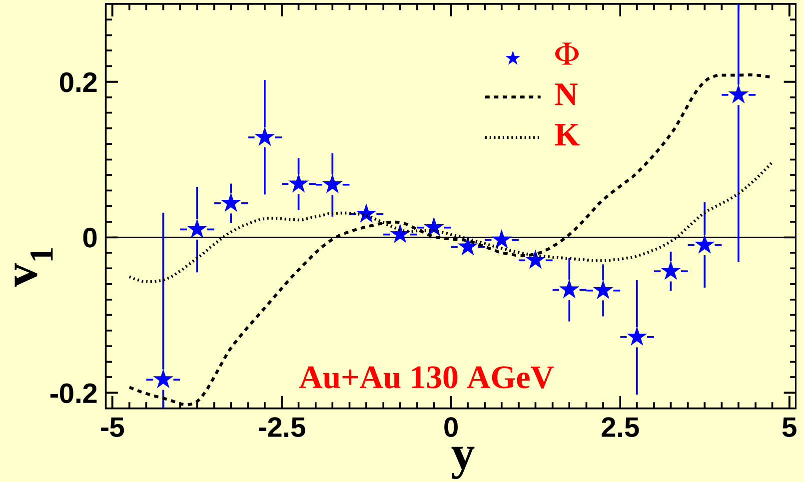
Development of Directed Flow

Resulting flow = normal flow - antiflow



L. Bravina *et al.*, NPA 715 (2003) 665c

Directed flow $v_1(y, all\ p_t)$ of ϕ, N, K in minimum bias Au+Au events at $\sqrt{s} = 130$ AGeV



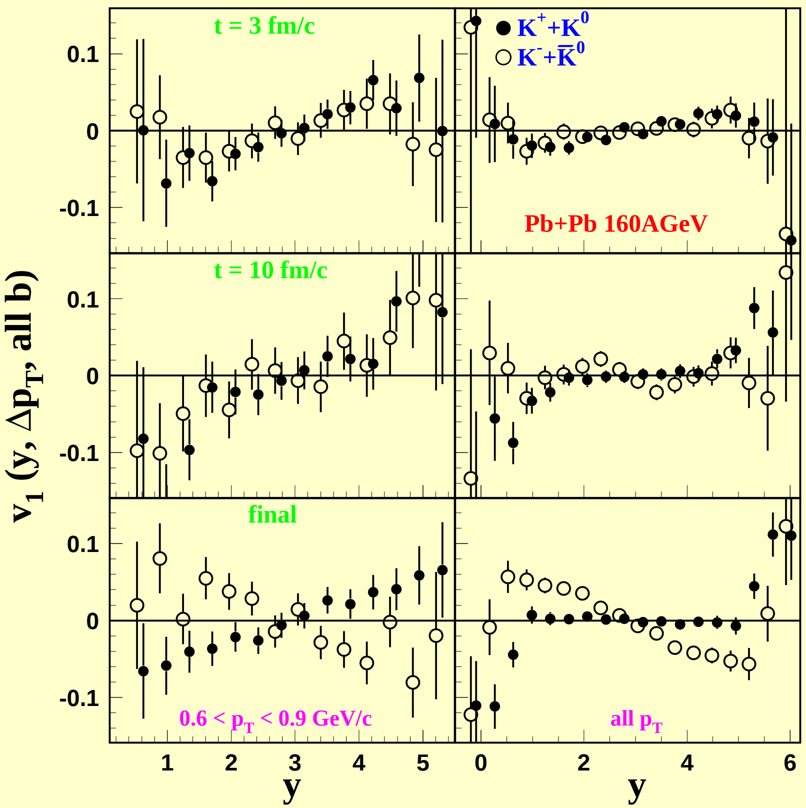
Although the normal flow component is always slightly larger than the antiflow one, in central rapidity window the antiflow can overshadow its normal counterpart

Directed flow of ϕ mesons $v_1(y)$ has negative slope (antiflow) at $|y| \leq 2$. This distribution is similar to those of other hadrons at $|y| \leq 2$ in $Au + Au$ at $\sqrt{s} = 130$ AGeV because of similarities of their production and dynamics

P_T Dependence of Directed Flow

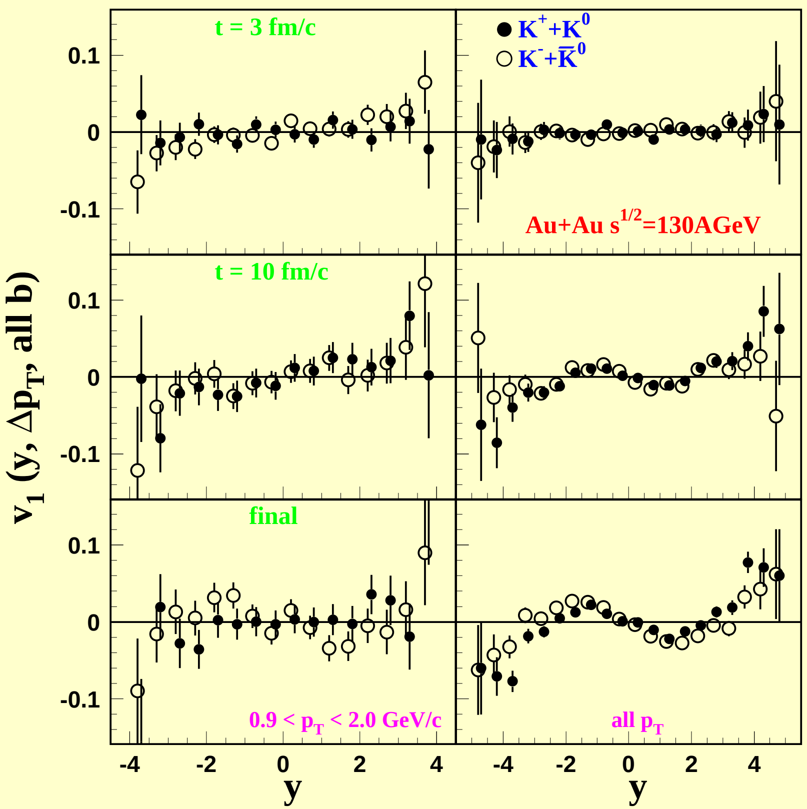
L. Bravina, L. Csernai, A. Faessler, C. Fuchs, E. Z., PLB 543 (2002) 217

Kaon flow at SPS



Strong difference between kaons and antikaons

Kaon flow at RHIC

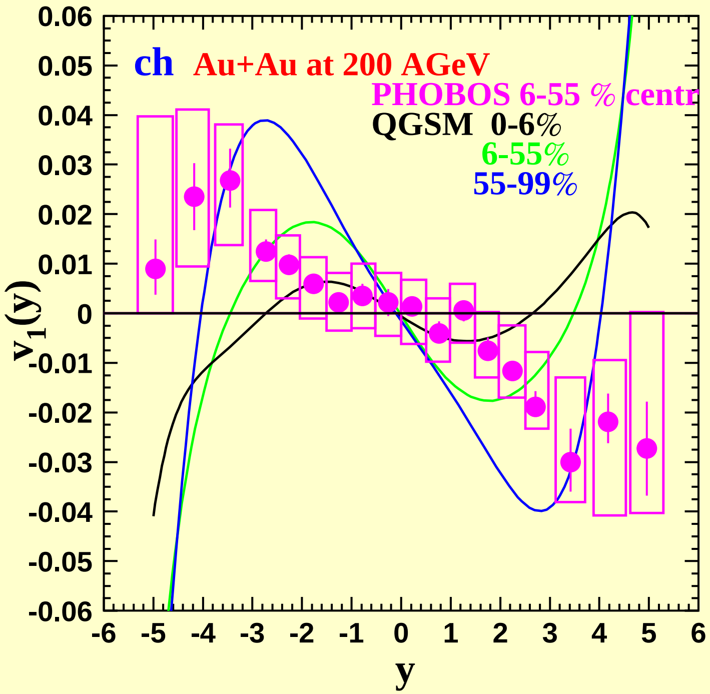


No difference between kaons and antikaons

Directed Flow at RHIC

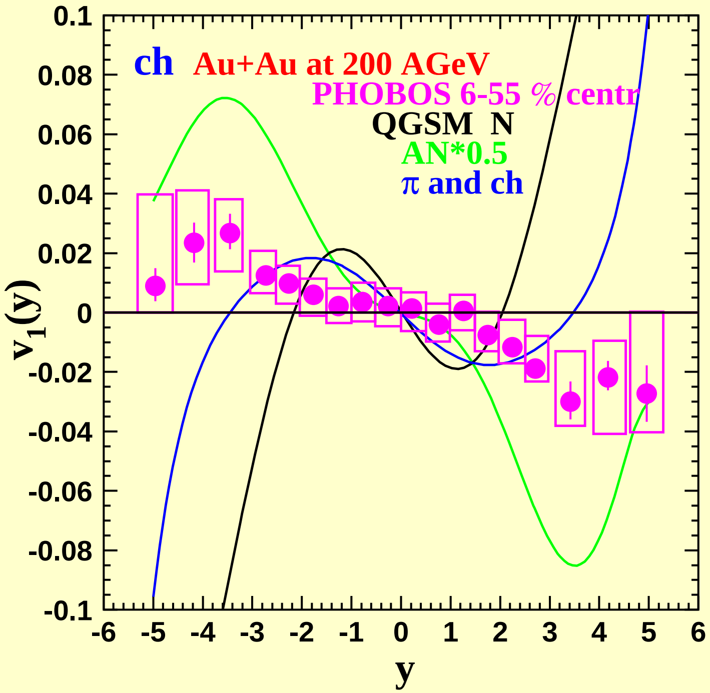
M.B. Tonjes *et al.* (PHOBOS Collab.), JPG 30 (2004) 1243

Centrality dependence of the DF of charged particles



(1) DF increases with rising b
(2) Exp.: antiflow increases up to fragmentation regions

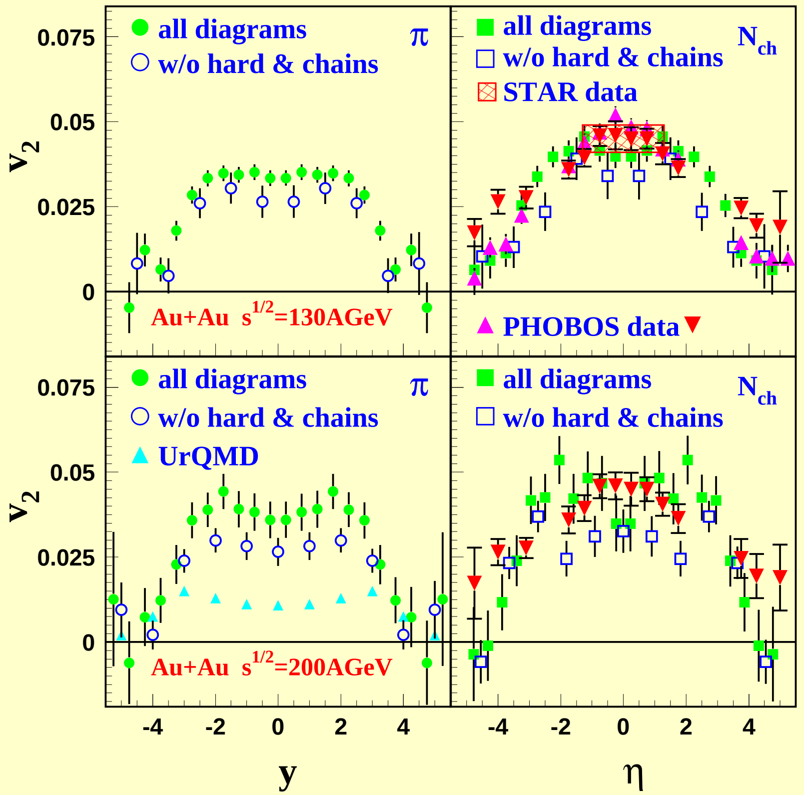
Directed flow of different species

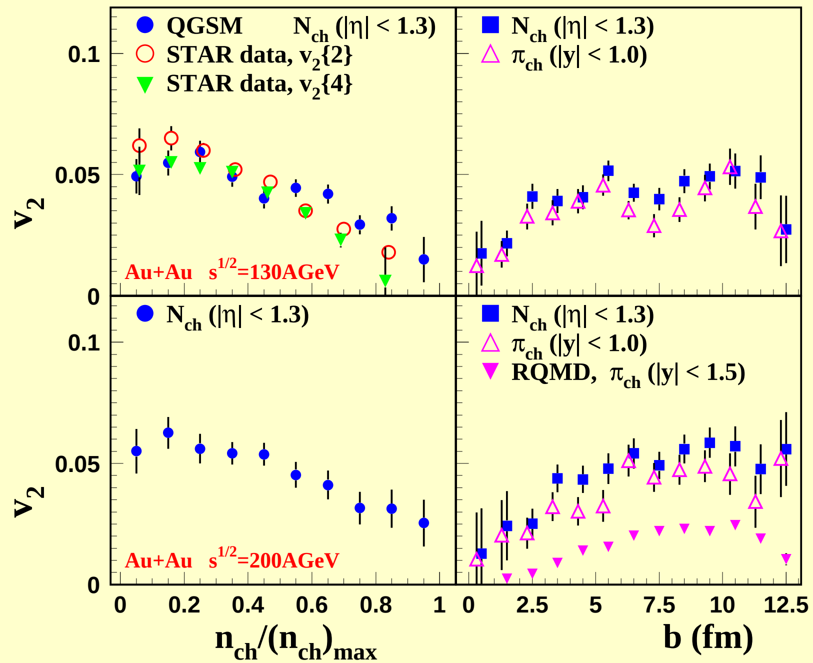


Antibaryons have strongest antiflow because of annihilation

Elliptic Flow at RHIC

E. Z., L. Bravina, A. Faessler, C. Fuchs, PLB 508 (2001) 184
PPNP 53 (2004) 183
M. Bleicher and H. Stöcker, PLB 526 (2002) 309
S. Manly et al., PHOBOS Collab., NPA 715 (2003) 614c



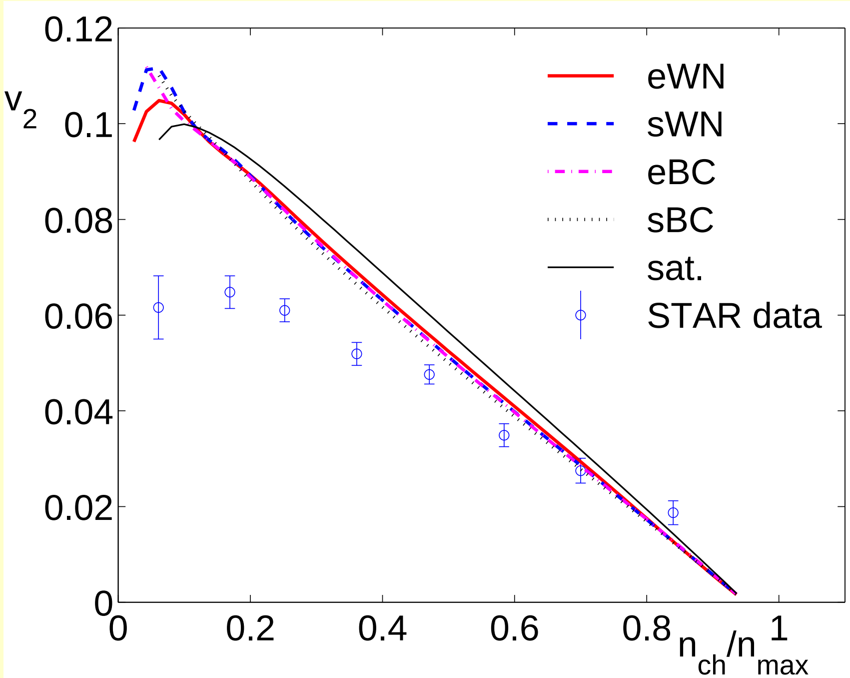


(Pseudo)rapidity dependencies of the elliptic flow of charged particles in the whole η range at both energies were obtained *before* the experimental data became available

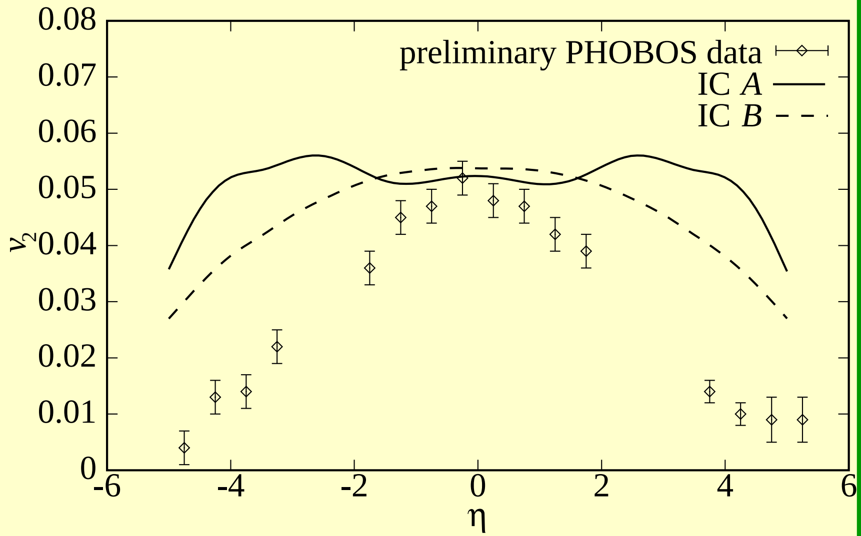
Elliptic Flow at RHIC (Hydro)

P. Huovinen et al., PLB 503 (2001) 58
T. Hirano and K. Tsuda, NPA 715 (2003) 821c

Centrality Dependence



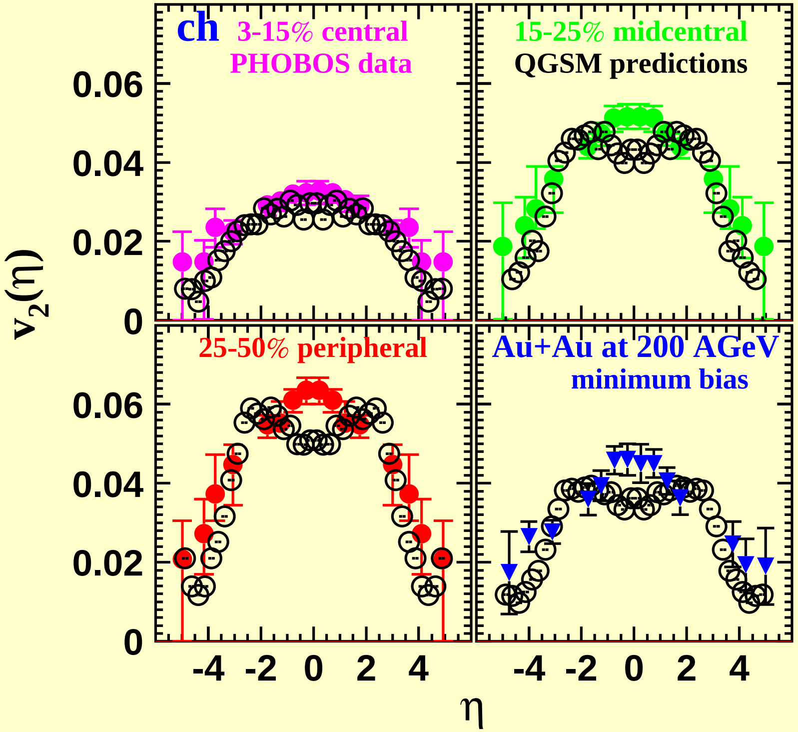
Pseudorapidity Distribution

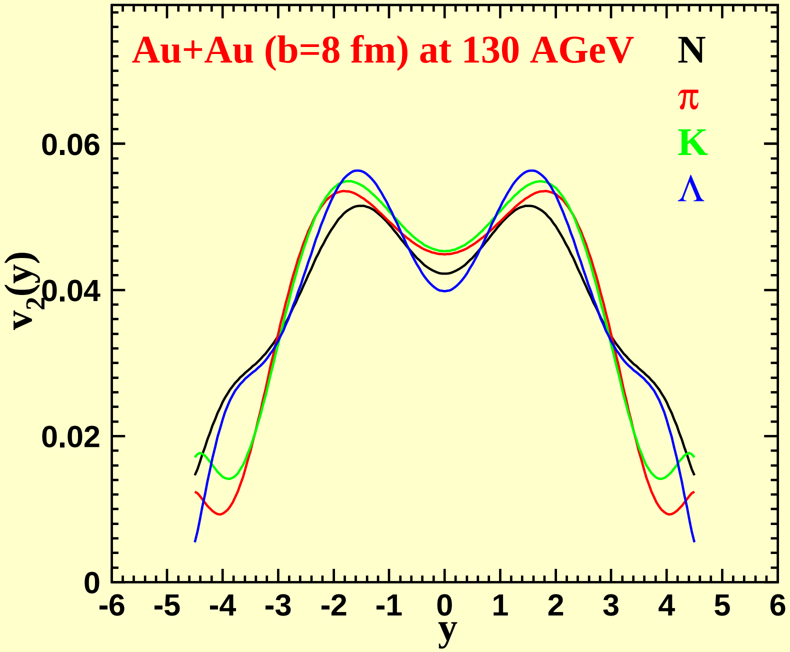


The agreement between the experimental distributions and model simulations is not good.

Elliptic Flow at RHIC

B. Back *et al.* (PHOBOS Collab.), nucl-ex/0407012





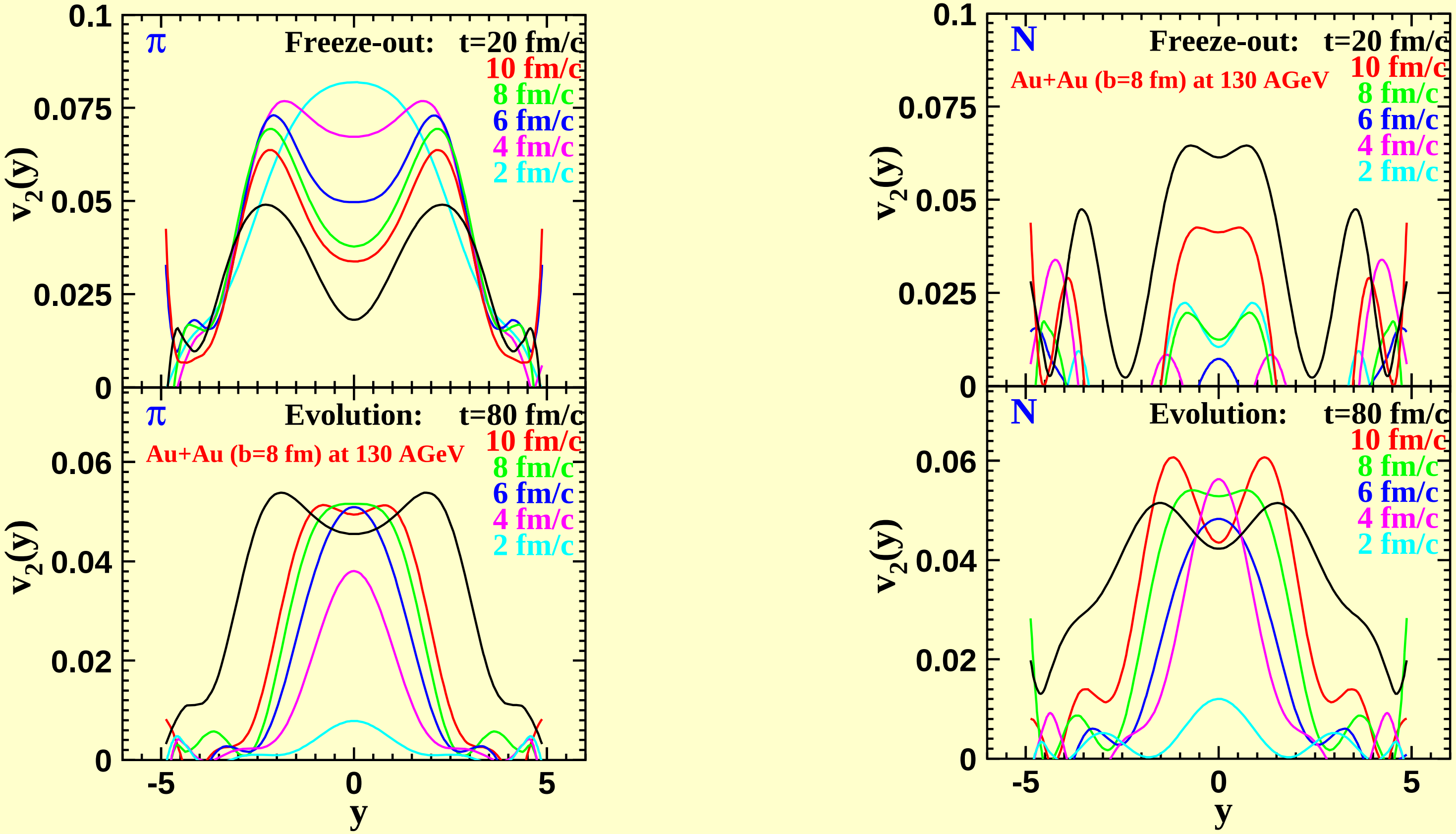
$v_2(\eta)$ **distribution of charged particles in Au+Au at** $\sqrt{s} = 200$ **AGeV for (a)** $\sigma/\sigma_{\mathbf{geo}} = \mathbf{0 - 15\%}$**, (b)** $\sigma/\sigma_{\mathbf{geo}} = \mathbf{15 - 25\%}$**,**

$v_2(\eta)$ **distribution of** $\pi, \mathbf{N}, \mathbf{K}, \boldsymbol{\Lambda}$ **in Au+Au at** $\sqrt{s} = 200$ **AGeV**

No difference for different species

Time Evolution of the Elliptic Flow

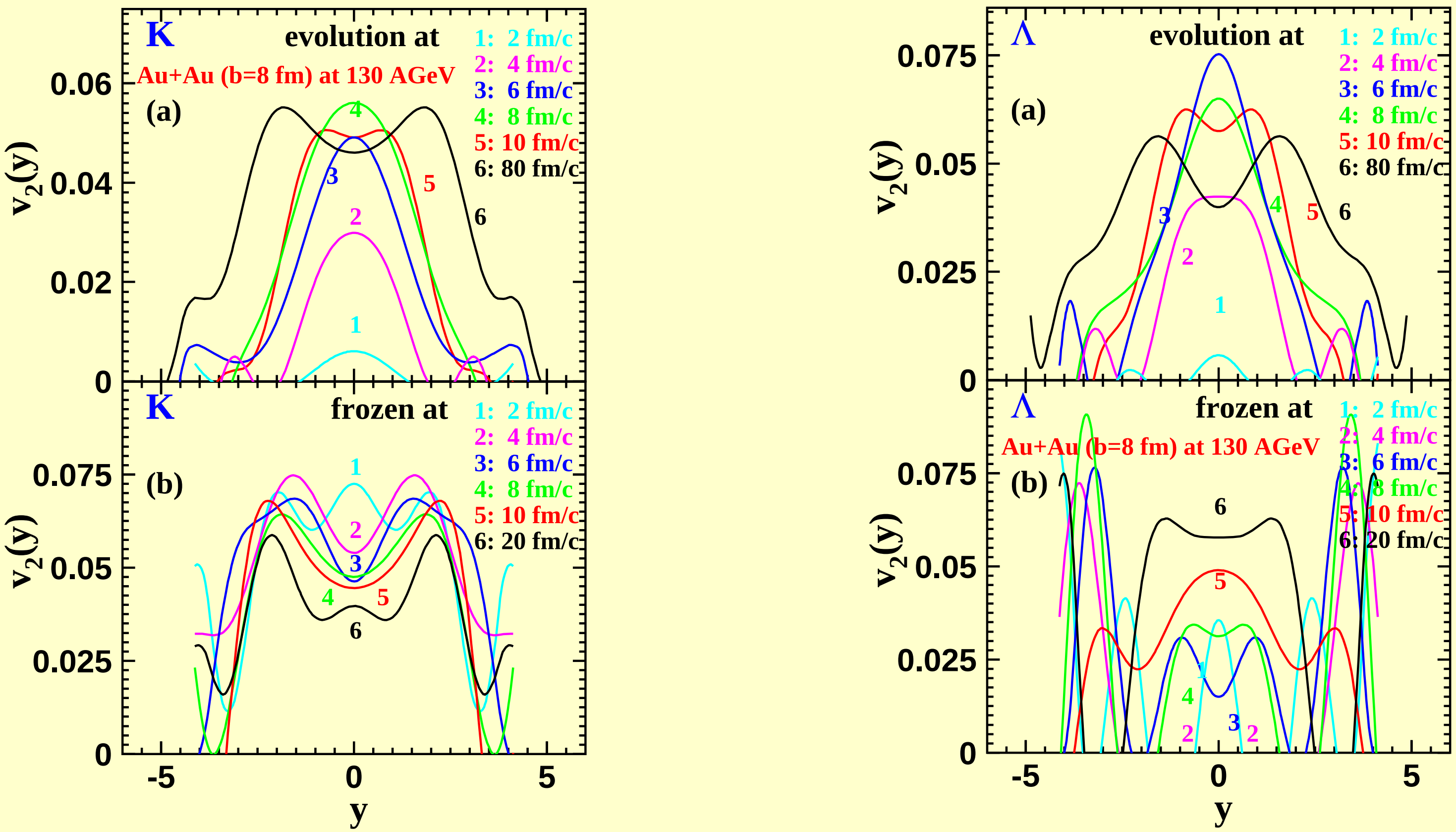
PIONS (Au+Au, 130 AGeV, b=8 fm) **NUCLEONS**



(1) The earlier the freeze-out of pions, the stronger their elliptic flow
(2) The later the freeze-out of nucleons, the stronger their elliptic flow
(3) The flow formation is not over e.g. at $t = 6$ fm/c due to continuous freeze-out of particles

Time Evolution of the Elliptic Flow

KAONS (Au+Au, 130 AGeV, b=8 fm) LAMBDAS



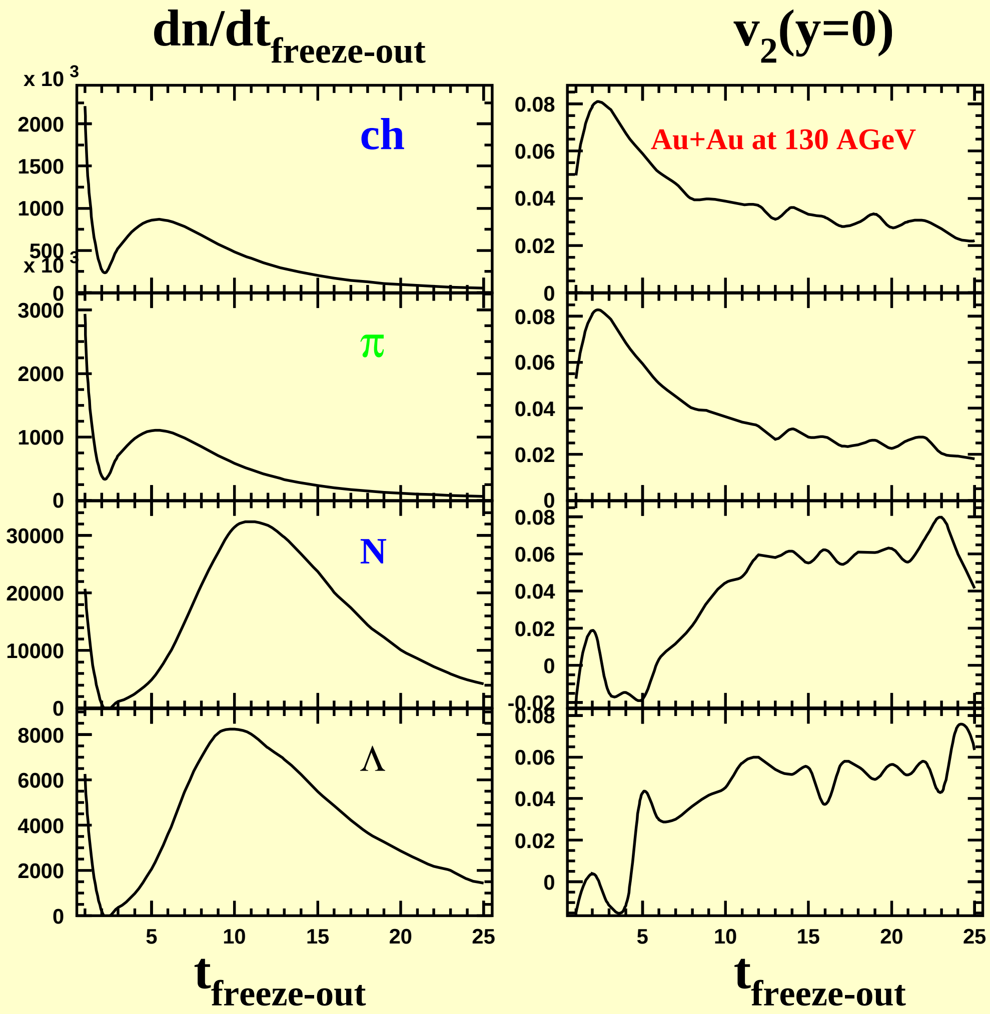
(1) The earlier the freeze-out of kaons, the stronger their elliptic flow

(2) The later the freeze-out of lambdas, the stronger their elliptic flow

This is the main difference in the formation of the elliptic flow of mesons and baryons

Freeze-Out and Elliptic Flow

Au+Au (b=8 fm) at $\sqrt{s} = 130$ AGeV

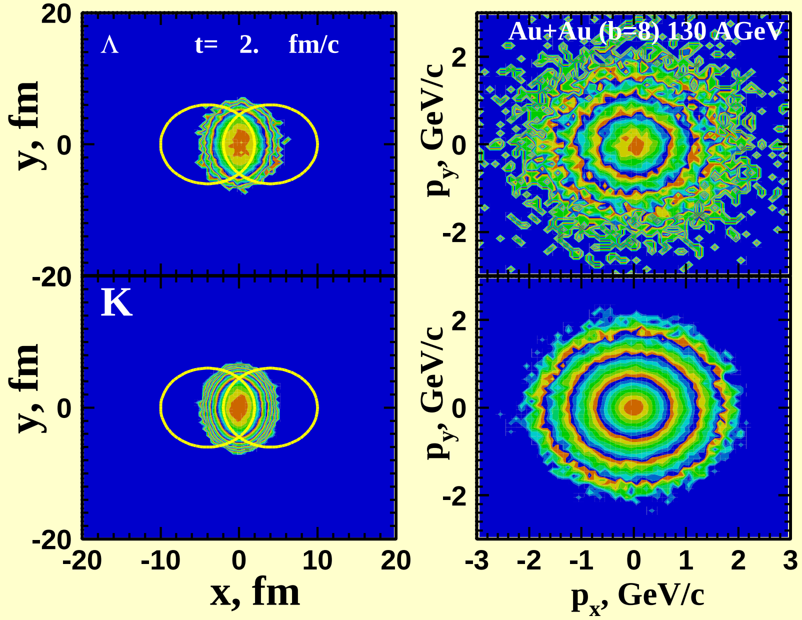


(1) Substantial part of hadrons leaves the system immediately after their production within the first two fm/c.
(2) Baryons and mesons are completely different: pions emitted within the first few fm/c carry the strongest flow. In contrast to pions, the baryon fraction acquires stronger elliptic flow during the subsequent rescatterings, developing the hydro-like flow.

Development of Elliptic Flow of K, Λ at RHIC

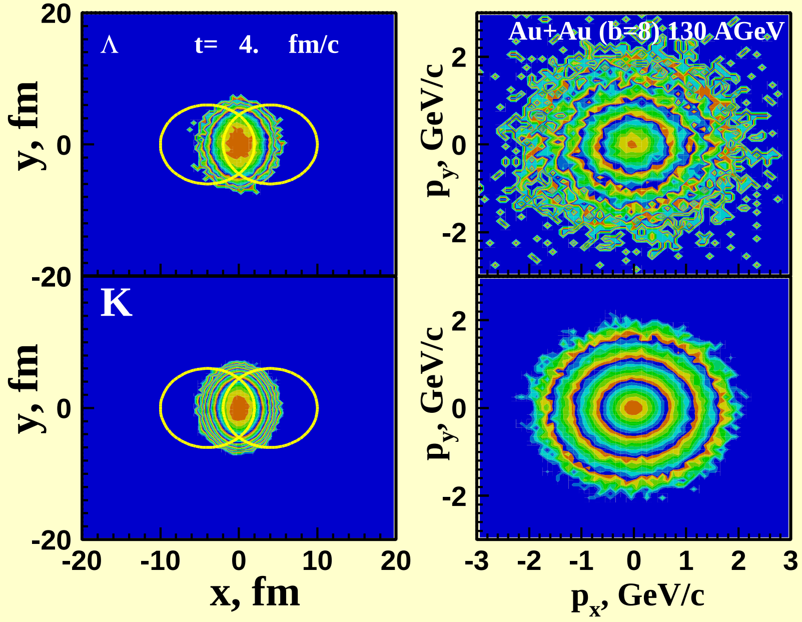
Anisotropy in coordinate space and elliptic flow of kaons and lambdas in Au+Au collisions at $\sqrt{s} = 130$ AGeV with the impact parameter $b = 8$ fm.

$t = 2$ fm$/c$



Strong anisotropy in coordinate space, but weak anisotropy in the momentum space

$t = 4$ fm$/c$

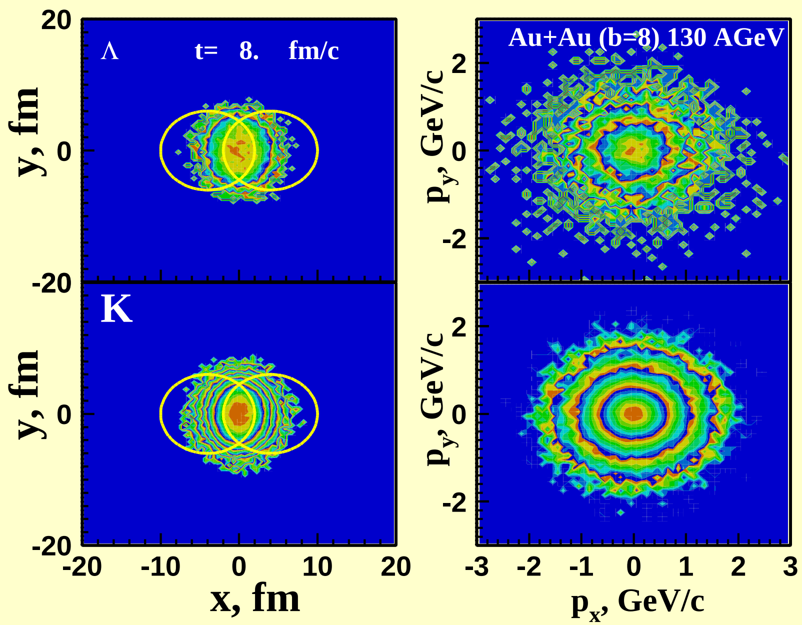


Anisotropy starts to develop in the momentum space for low momenta

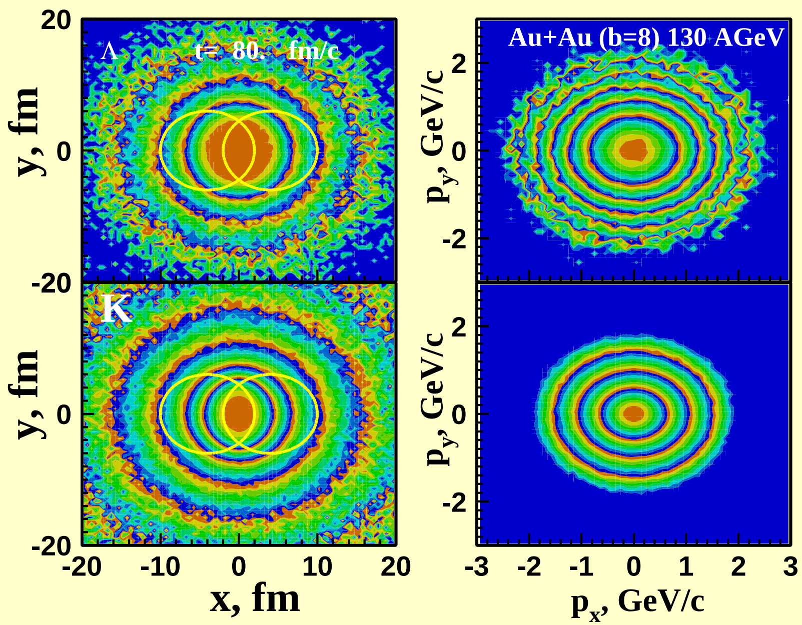
Development of Elliptic Flow at RHIC

Anisotropy in coordinate space and elliptic flow of kaons and lambdas in Au+Au collisions at $\sqrt{s} = 130$ AGeV with the impact parameter $b = 8$ fm.

$t = 8$ fm/c



final



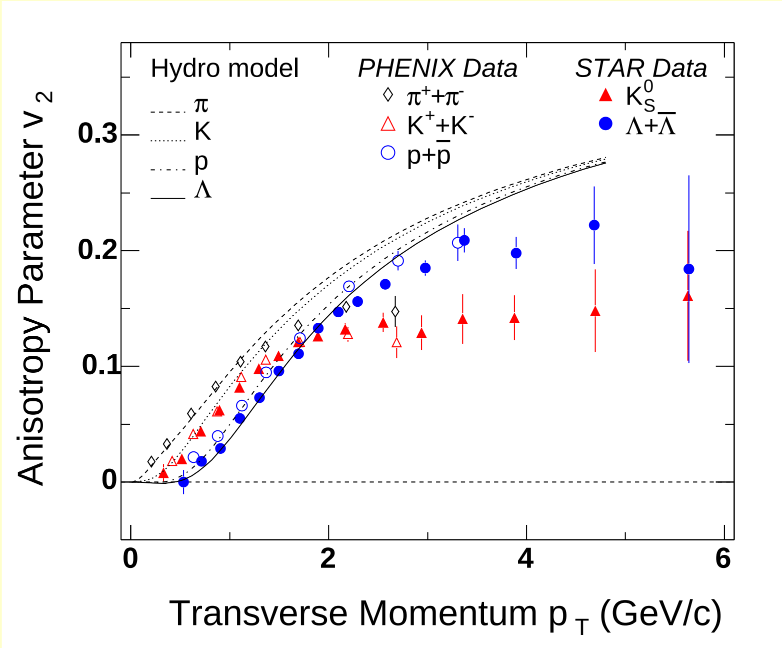
$\mathrm{d^2N/dxdy}$ for Λ at 80 fm/c has wide plateau between centers of colliding nuclei. $\mathrm{d^2N/dxdy}$ for kaons is much narrower; like pions, kaons are mostly concentrated in the overlapping region

The momentum-space anisotropy for baryons is much stronger than that for mesons

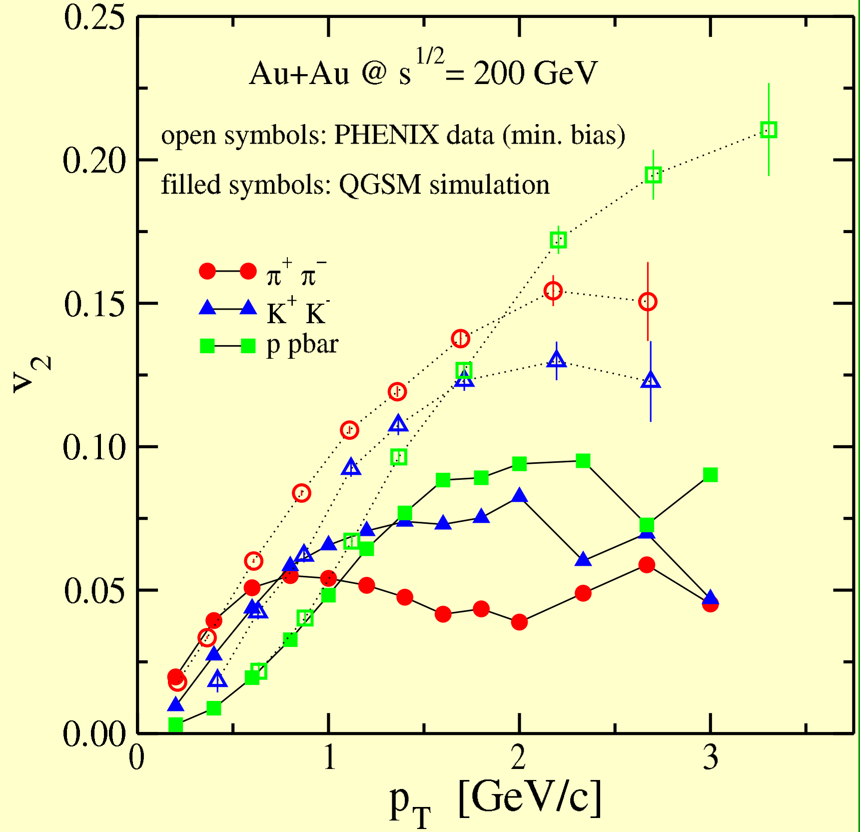
Elliptic Flow at RHIC

Hydrodynamics:

P. Huovinen *et al.*, PLB 503 (2001) 58
T. Hirano and K. Tsuda, NPA 715 (2003) 821c



QGSM:



(1) QGSM reproduces at least quantitatively the experimental evidence of crossing of the elliptic flow for mesons and baryons

(2) However, the magnitude of the $v_2(p_t)$ distribution is underestimated

Possible explanation: jets (?!)

Conclusions

Directed flow:

- Directed Flow = Normal Flow − Antiflow
  Normal Flow $\geq$ Antiflow (except of the midrapidity range because of Shadowing)
- The softening of the flow may be misinterpreted as the softening of EOS due to formation of the QGP, but:
  QGP $\rightarrow$ the effect is stronger for semi-central collisions
  Shadowing $\rightarrow$ the effect is stronger for semi-peripheral and peripheral ones
- At RHIC: The directed flow of both mesons and baryons is antiflow-oriented at $|y| \leq 2$

Elliptic flow (EF):

- EF of hadrons increases with rising P_T
- EF at $y = 0$ reaches maximum at $t \approx 8$ fm at RHIC
- Elliptic flow depends strongly on particle freeze-out. The earlier the freeze-out of mesons, the stronger the $v_2^M(y=0)$, while the v_2 of baryons frozen earlier is weaker than the v_2 of baryons frozen later on